Development of Lightweight X-Ray Mirrors for the Constellation-X Mission

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ABSTRACT

One of the most important aspects of the Constellation-X x-ray optics development is the fabrication of lightweight mirror segments. Given its multi-faceted requirements, i.e., good angular resolution, light weight, and low production cost, we have adopted a glass slumping or forming technique that takes advantage of the naturally excellent microroughness of thin float glass sheets. In this paper we present measured quantities of formed mirror segments and compare them with requirements to show that the formed mirror segments have met all except the sag requirement. The larger than acceptable sag error may be an artifact of the measurement process. It may also be caused by coating stress or residual thermal stress resulting from the slumping process. Our immediate future task is to identify the source(s) of the sag error and address them accordingly.

Keywords: X-ray optics, lightweight optics, Constellation-X, space optics

1. INTRODUCTION

Requirements of the Constellation-X mission on its x-ray mirror assemblies are multi-faceted. On the one hand, it requires good angular resolution. On the other hand, it also requires an unprecedented amount of mirror area. Both of these requirements must still be met with an overall mass budget derived from capabilities of existing launch vehicles. In a nutshell, these requirements mean the mirror segment has to be as thin as 0.4mm. Affordability also means that the production process has to be relatively simple and straightforward, amenable to scaling up to industrial scales.

We have adopted a glass slumping technique to meet all these requirements [Zhang et al., 2006, 2005, 2004, and 2003]. This technique, by design, meets every requirement except the angular resolution requirement. Therefore our task has been to understand the slumping process and improve its accuracy.

Our development strategy has been: (1) to achieve repeatability and then (2) to achieve accuracy. Repeatability means that every mirror segment needs to be made like every other mirror segment, showing that the process is highly reliable and with as little randomness as possible. Accuracy means that

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every mirror segment needs to be like the mandrel on which it is formed, with as little systematic error as possible.

As shown in Zhang et al. (2006), excellent repeatability and accuracy were achieved. In this paper, emphasis is given to comparing mirror segment properties with Constellation-X requirements.

Table 1 lists the requirements (or error allocations) of the most important quantities that have been measured of each mirror segment. This represents a modification to previous scenarios [Zhang et al. 2006 and 2005] in that all quantities in this table are operationally defined, as opposed to previous quantities that are based on purely mathematical analyses. While Table 1 does not contain a mathematically complete set of quantities needed to describe a mirror segment, it does have all the practical information necessary to make definitive x-ray performance predictions. In the next section, we will describe each of these quantities and present data to show where our development program stands.

Table 1. A practically complete set of quantities that characterize a mirror segments. See text for detailed descriptions of these quantities. Numbers in red are contributions to the two reflection image HPD.

Quantity		Error Allocatio	Measurement Method		Comment
Average radius		20um	STIL Cylindrical Coordir Measuring machine		Can easily achieve ~10 micr accuracy
Focal length (average cone angle and radi		0.5mm	Grazing incidence bea (Harmann test)		Can easily achieve ~0.5 mm accuracy
Focus Quality (cone angle and radius variati		4.0"	Hartmann test	Phase-measurin interferor eter and null lens	Can easily achieve sub-arcsecond accuracy
Sag (P-V magnitude of 2nd orde		4.0"	Axial Scans using an interferomet		Accuracy determined by mir mount repeatability/accurac Measuring instrument can ea do ~50 nm
Axial Figure	Low Frequency Figur (200mm-20mm)	8.8"			Can easily achieve the requi accuray
	Mid-Frequecy Figure (20mm-0.2mm)				Overlap regime between twc instruments; Detailed and quantitaive comparison alwa needed
	High-Frequency Figu (0.2mm-0.001mm)		Zygo Newview 5000 surface profiler		Can easily achieve 0.3nm RM measurement
HPD of Mirror Pair		10.5"			

2. STATUS OF MIRROR SEGMENT FABRICATION

In this section, we will describe each of the quantities in Table 1, the way it is measured, and how the manufactured mirror segment compares with requirements.

2.1 Average Radius: It determines the radial position of the mirror segment in the mirror assembly. Error in this number typically causes a reduction in effective area. Depending the specific shell involved, a 20µm error in average radius means ~1% reduction in effective area.

The average radius is measured with a cylindrical coordinate measuring machine (CCMM) [Lehan et al., 2007] which has been custom-designed and –built for our project by STIL. In general, to the extent we can measure, the mirror segments as fabricated meet the average radius requirement.

2.2 Focal Length and Focus Quality: Theoretically focal length is determined by a combination of average radius and average cone angle. With a whole shell mirror, any two of these three variables can uniquely determine the third one. With a mirror segment, the cone angle is somewhat correlated with the tilt which is external to the mirror segment. In particular this correlation depends on the angular size of the mirror segment. If the angular size is small or close to zero, the concept of cone angle is nearly meaningless. It can be completely replaced by an external tilt. If the angular size is 360 degrees, in other words, a whole shell, it is uniquely and unambiguously determined.

Since the mirror segment we are developing is between 30 and 60 degrees, which is a fairly small fraction of a whole shell, the above consideration dictates that the meaningful question to ask is: once placed at the expected focal length and expected radial position, does the mirror segment produce an acceptable image on the focal plane, after appropriate tilt adjustment? This question is answered with a series of Hartmann tests [Hadjimichael et al., 2007]. These Hartmann tests measure the focal centroid of each mirror sector. As shown in Figure 1, the mirror segment has all its sectors focus to a singe point with an RMS radius error only 1.5 arcseconds. They typically meet requirements.

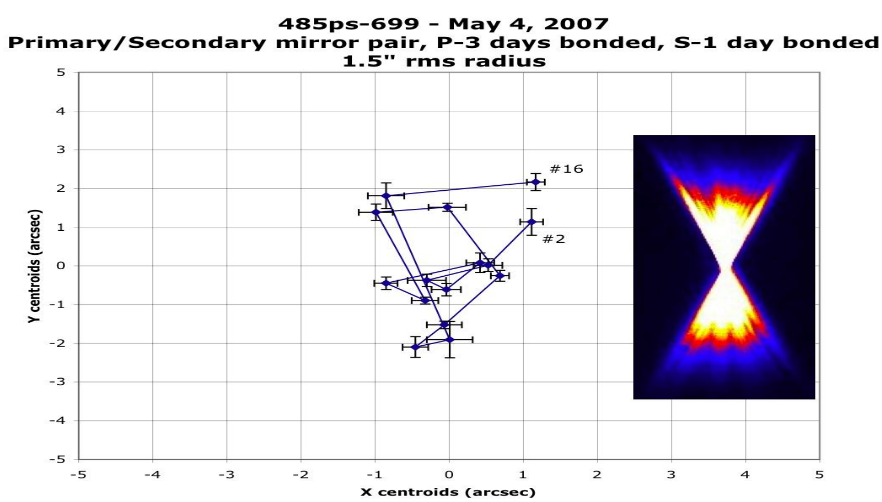

Figure 1. Hartmann map of a pair of mirror segments placed on a mattress designed to balance out gravity distortion. This image represents the best achieved so far. The typical number is 2 to 3 arcseconds rms radius, meeting or exceeding the 4.0 arcseconds HPD requirement.

2.4 Sag: The Constellation-X mirror assemblies require true Wolter-I mirror segments, as opposed to conical approximations. The measurement of a mirror segment's sag is plagued with uncertainties, most of which are due to distortion by gravity and other forces inadvertently introduced during measurement. Recent progress with a Cantor-tree mount [Lehan et al., 2007] appears to give reasonable repeatability from one measurement to another, as shown in Figure 2.

The variation of sag across the azimuth is slightly too large to be acceptable. At present time, it is not clear whether the curling-up and sag near the mirror edges is due to the mirror or is something related to the measurement process. The reasonable repeatability from measurement to measurement seems to indicate it is something very systematic.

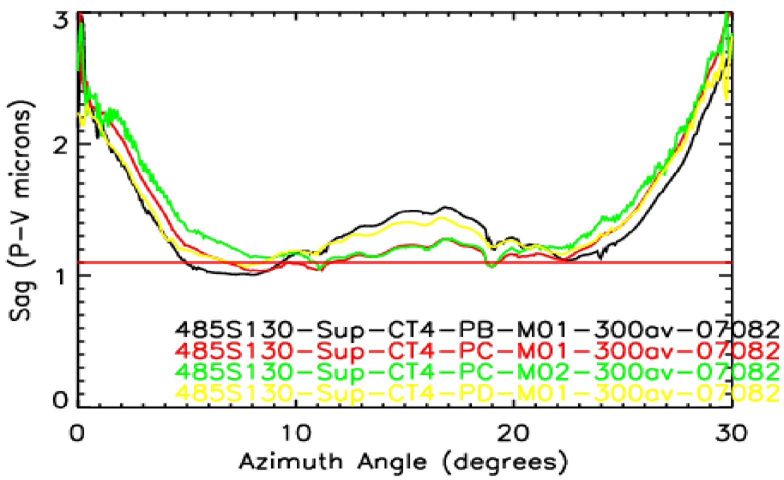

Figure 2. Sag vs. azimuth angle measured of a 30-degree mirror segment. The four different curves represent four different measurements, indicating the degree of measurement repeatability. The red line indicates the design sag, which is 1.1 μm across the entire azimuth.

If the variation with sag is on the mirror itself, as opposed to being an artifact of the measurement process, there are two likely sources of contributor. The first one is that the glass has too high an internal stress resulting from the thermal slumping process. The second potential contributor is the coating process. The mirror segment is coated on one side with Ir, which in principle, can cause the observed sag characteristics. In either of these two cases, the error can be corrected by a balancing coating on the other side of the mirror.

2.5 Axial Figure: Axial figure is expected to be largest contributor to the final image quality. Figure 3 shows the complete PSD of a typical axial figure measured over the spatial frequency band of 0.05 mm^{-1} to 100 mm^{-1}, corresponding to 200mm to 10μm in spatial period.

In Figure 3 the blue data curve comes from axial scans acquired with an ADE-Phaseshift Fizeau interferometer. Its response bandwidth stops being adequate above spatial frequency 0.2 mm^{-1}. The black data points come from a Zygo Newview 5000 surface profiler which, in its 2.5X configuration, covers the spatial period between 10µm and 2.8mm. The teal curve is representative of a typical D263 glass sheet as it arrives at our laboratory.

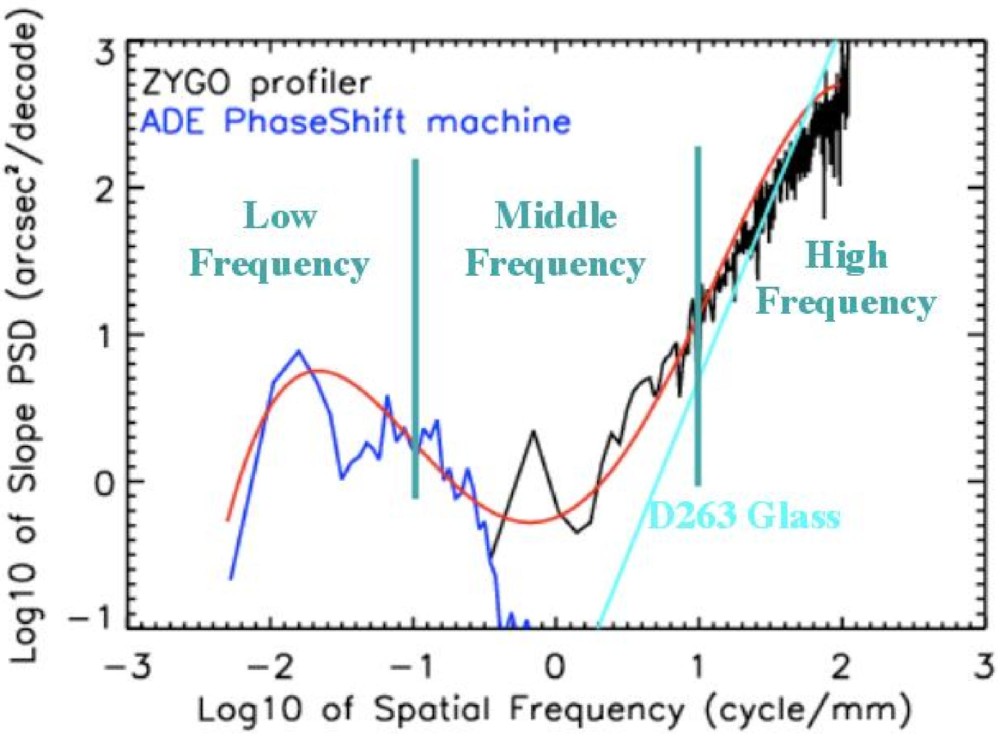

Figure 3. PSD of a typical axial figure measurement. The entire spatial frequency band can be broken into three regimes: low, middle, and high. See text for significance of discussions of these three regimes. The red smooth curve is a fit to a representative set of measurement, which is slightly different from the one that is plotted here.

Table 2. Two-reflection x-ray image expected from the red curve in Figure 3. The grazing angle used for the computation is 0.4 degrees. The final result of 8.7" meets the requirement as outlined in Table 1.

Energy (keV)	Wvlength (A)	Two Reflection HPD (arc-sec)
1.00	12.40	8.13
2.00	6.20	8.49
3.00	4.13	8.37
4.00	3.10	8.65
5.00	2.48	8.69
6.00	2.07	8.81
7.00	1.77	9.17
8.00	1.55	9.45
	Average	8.72

The entire spatial frequency band of interest can be divided into three regimes. In the low frequency regime, covering spatial periods from 200mm to ~10mm, the ADE-Phaseshift machine is quite adequate in measuring the axial figure. The mirror segment figure closely resembles that of the forming mandrel. In other words, better mandrels will lead to better figures in this regime. In the high frequency regime, covering spatial periods from 0.2mm to 10μm, the mirror segment figure resembles that of the pristine D263 glass sheet. In other words, the thermal slumping process does not alter the excellent microroughnes of the glass sheet. In the middle frequency regime, covering spatial periods from ~10mm to ~0.2mm, the two measuring instruments overlap. Neither of them gives adequate coverage. One has to rely on a measure of interpolation and extrapolation to decipher the true figure of the mirror segment. Nonetheless it is clear that the mid-frequency figure of mirror segment depends on the slumping process.

Table 2 shows the computational results of x-ray image quality expected from the PSD shown in Figure 3. In a nutshell, the axial figure contribution to the image quality is 8.7" HPD (two reflection equivalent), meeting requirements.

3. PROBLEMS AND SOLUTIONS

The discussions and comparisons of the last section clearly indicate that our highest priority is understanding the sag of the formed mirror segments. This problem is at the intersection metrology and fabrication. First, it is necessary to isolate the problem. There are at least three possible contributors to the apparent sag error: (1) mirror distortion caused during the measurement process by either gravity or other forces as part of the mirror mounting; (2) the Ir thin film coating process; and (3) residual stress resulting from the thermal forming process.

To address the first potential problem, we will support or fixture the mirror segment in at least three different ways [Zhang et al. 2007]. If the mirror segment's sag is measured to be the same no matter which is used to support it, we will conclude that he sag error is probably of the mirror segment itself. In other words, it is caused either by the coating process or by the thermal slumping process. In either case, the most effective way to correct the sag error may be to use a layer of balancing coating on the other side of the mirror. We will use finite analysis techniques [Chan et al. 2007] to design a coating pattern and implement it with a sophisticated baffling procedure that has been developed for making multiplayer coatings.

4. ACKNOWLEDGEMENTS

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